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1. Introduction

In a technical study summary of the same title as this (hereupon called Part I) of the 1981 Technical Report (Ref. 1), the results of laboratory scale experiments on subsurface oil collectors are described. The collectors were of the inverted funnel-type intended for use immediately above the wellhead or blowout source. It was found that the fraction of blowout oil collected was primarily dependent on the Froude number F, and the phase ratio R, with these quantities defined by

$$F = Q_T/(gh^5)^{\frac{1}{2}} \tag{1}$$

$$R = Q_T/Q_g \tag{2}$$

where Q_T is the total collected liquid flow rate passing through collector and riser,
Q_g is the gas volume flow rate,
g is the acceleration of gravity
h is the vertical distance from the blowout source to the base of the collector.

So long as nearly all of the blowout gas was collected, the fraction of blowout oil collected was found to be relatively insensitive to details of the collector shape. When the collector was made small enough for a substantial portion of the gas to avoid collection by rising beside the collector, an increase in fraction of blowout oil collected was often observed to occur. This led to the conclusion that under many circumstances, a collection system could encounter more than the optimum amount of gas. To aid in overcoming the reduction in collection efficiency resulting from excess gas, a gas separating collector was devised. Preliminary laboratory experiments with the gas separating collector are described in Part I. Now, further experiments with the laboratory scale model of the gas separating collector have been carried out and are described in the next section of this paper.

The laboratory scale experiments described in Part I have a length scale of approximately 1/15'th of anticipated full scale. Now, intermediate scale experiments at approximately 1/4th of full scale have been completed and these are described here.

2. FURTHER EXPERIMENTS WITH THE GAS SEPARATING COLLECTOR

Figure 1 shows a drawing of the laboratory model of the gas separating collector. As is described in Part I, it was initially planned that this collector would operate with most of the gas passing through the central riser with just enough gas escaping from the inner cone to the outer cone to drive the outer riser at maximum efficiency. The data presented in Part I were obtained for these conditions.

To operate a gas separating (henceforth called double) collector in the above way requires adjustment of the inner rise resistance, by means of a control valve, to make it suit the operating conditions. Subsequent experiments in the laboratory revealed an efficient mode of operation which did not require such an adjustment. This was to fit both the inner and outer collector with equal size risers and to collect liquid from both risers. Under efficient conditions having a high liquid flow and a small amount of gas, no gas would escape from the inner collector and only the inner riser would pump liquid. If the gas flow is increased from that yielding an efficient operating condition, some gas escapes from the inner collector to the outer collector and the outer riser begins pumping. With both risers operating, the total collected liquid flow rate increases which yields an increased Froude number and a higher efficiency. If the amount of gas is increased still further, the inner collector will choke and pass only gas while the outer riser pumps liquid as a result of the gas lift from that gas which escapes from the inner collector. This condition, for extremely large amounts of gas, is precisely the condition for which the double collector was initially designed.

To test the double collector in the "automatic mode" described above, the model shown in Figure 1 was fitted with two identical risers each having an inside diameter of 3.38 centimeters. Water and oil from each riser were collected and measured in the manner described in Part I and the Froude numbers and phase ratios were based on the sum of the liquid flow rates in the two risers. Table 1 shows the Froude numbers, phase ratios and oil collection percentages obtained for this series of tests. The table also shows the predicted collection percentage for a single collector operating at the same Froude number and phase ratio, as given by equation (2) of Part I.

3. INTERMEDIATE SCALE TEST APPARATUS & PROCEDURES

Intermediate scale tests were conducted in Bugg Spring which is a natural sinkhole spring having a depth of 53 meters and a mean surface diameter of 110 meters, located at Okahumpka, Florida and which is part of the U.S. Naval Research Laboratory.
Figure 2 shows drawings of Bugg Spring and the position of the tightly moored barge that was used as the work platform. Figure 3 shows the layout of the apparatus and equipment that was used for the experiments.

The previous laboratory experiments showed that upon exiting from the wellhead, the oil was broken down into droplets having diameters much less than 1 millimeter which were then mixed into a volume of water much larger than that of the oil. The oil then acts as a "tracer" for the resulting water flow. This finding was used for the Bugg Spring experiments inasmuch as it was not feasible to pump oil into the spring. The tracer used instead was water soluble fluoroscein dye which was mixed with water in tanks on the barge to a concentration of approximately 10 parts per billion. The extremely high sensitivity of fluorometric detection techniques permitted quantitative determination of the fraction of blowout tracer collected and this coupled with the fact that any dye remaining in the spring was ultimately broken down into colorless components by sunlight made fluoroscein the "ideal tracer".

In the earlier laboratory scale tests, it was found that the fraction of blowout oil collected was independent of the blowout oil flow rate. This is consistent with the concept of the oil acting as a tracer in the water flow. Initial tests carried out with the intermediate scale collection systems also showed that the fraction of dye flow collected was independent of the dye flow rate. Following these tests, a nominal dye flow rate of 2.3 liters per second was used.

The blowout gas was simulated by air supplied from an air compressor fitted with valves and an air bleed off arrangement so that any flow rate up to 0.71 standard cubic meters/second (1500 SCFM) could be supplied to the 7.6 cm I.D. hose leading to the barge. The air flow rate to the wellhead was monitored by an orifice meter mounted on the deck of the barge with pipes and hoses running from it to the wellhead.

The collector-wellhead assembly shown in Figure 4, was attached to the base of the collector. The wellhead to collector base height could be varied from 0.04 to 2.0 meters by adjusting a wire rope cable on the surface which ran down the riser and was attached to the wellhead through a system of sheaves. The collector base remained fixed at 46 meters below the surface during all experiments.

During the intermediate scale model experiments, three different collector configurations were tested: A single collector, a double collector, and a straight riser pipe collector. The single and double collectors were built to have the same general shape as the collectors used in the laboratory experiments, but were scaled to be four times as large. The straight riser pipe collector held the same scale in that its internal diameter was the same as the riser pipe used for the single and double collectors. Laboratory scale tests indicated that a riser alone could collect a significant percentage of blowout oil. The use of a riser without a collector offers advantages in certain field applications where a surface fire, caused by escaping gas which is not collected, can be tolerated. Therefore this configuration was included in the test program.

One major structure, the outer-single collector and header box, was constructed to accommodate all three different collector configurations. This structure also incorporated pipes which transported the simulated oil and gas, from the hoses lashed to the risers, to the wellhead. Figure 5 shows the details of the double collector. The inner collector was bolted to a flange which was attached to a pipe that ran through the header box and formed the inner riser. The outer collector, which also formed the single collector, was built under the header box which had six 10.2 centimeter diameter holes in its bottom. These holes allowed the passage of gas and liquid from the outer collector of the double collector system into the outer riser pipe bolted to the top of the box.

During the testing of the single collector, the inner collector from the double collector system was unbolted from the inner flange, thereby forming a single collector. The holes in the bottom of the header box were plugged with pipe plugs. The inner riser pipe of the double collector then became the single collector riser and the outer riser was removed from the system.

To test the straight riser pipe, the six plywood side panels of the single-outer collector were removed. This condition left a steel support frame so that the wellhead remained supported. A 20 centimeter diameter pipe 1.2 meters long, which equalled the collector height, was bolted to the inner flange on the bottom of the header box. This pipe then served as the riser pipe collector. Figure 6 shows the riser pipe collector configuration.

The 20.3 cm ID riser pipes, ran from the top of the header box to the surface. Either one or two riser pipes were used, depending upon which collector configuration was being tested.

On the top of each riser, a swivel joint was incorporated into the system which allowed the riser spigots to be rotated in a horizontal plane so that liquid flow rates could be determined by measuring collected volume and time. Above the swivel joints, each spigot was formed by a 90° elbow with a pressure gauge mounted in it, followed by a butterfly valve for adjusting riser resistance. Each valve was followed by a section of pipe approximately 1.3 meters long which was connected to another 90° elbow to direct the flow downward. The entire system had an internal diameter of 20.3 centimeters.

As shown in Figure 7, the collector system was anchored to the bottom by three moorings. A fourth wire rope attached to the top of the collector ran to the barge and was tensioned to a force of one ton.

For each collector test, with known values of wellhead distance, dye concentration, dye delivery rate and air delivery rate, the additional qualities to be measured were liquid collection rate and dye concentration in the collected liquid. The liquid collection rate was determined from the time required to collect a known volume of liquid. Two open top tanks having a volume of $1.9m^3$ were constructed and installed on the barge. These tanks were fitted with sight glasses and were calibrated with a volume scale on each sight glass. One tank served each of the riser spigots. To measure a volume flow rate, a spigot was swung over a tank for a measured time interval and the collected volume during this interval was measured.

Dye concentrations were measured with a Farrand Model A-4 fluorometer. This instrument was fitted with a 490 nanometer interference filter for excitation of the sample and a Farrand Model 3-69 filter for the sample emission.

The double collector was tested at 13 operating conditions; the single collector at 16 conditions; and the riser along without a collector was tested at 14 operating conditions. Operating conditions and measured quantities are shown in Tables 2, 3 and 4. Each test was initiated by setting a nominal air delivery rate to the wellhead. A nominal liquid flow rate was set by the dye system control valve, but at this time dye was not delivered to the dye pump. Rather, the inlet of the pump was supplied from the Bugg Spring water itself so that operating conditions could be first established without any dye tracer in the flow. The riser valves were adjusted to provide the desired riser resistance.

After gaslift pumping was established, the system was allowed to operate in this condition for several minutes to flush any dye from previous tests out of the riser and collectors. Next, samples of the water delivered by the riser spigots were taken to be later used in the analysis for the fraction of blowout dye recovered by the collection system. The inlet to the dye delivery pump was then switched to the dye tank so that a dye stream was provided to the wellhead. The system was allowed to operate in this fashion for two minutes which was long enough to allow the liquid in the risers to be exchanged several times and thereby insure that dye concentrations delivered by the riser spigots were the same as the concentrations of the material collected by the collectors. During this time actual air flow rate and dye flow rate were measured and recorded. In addition, a sample of the dye solution in the dye tank was taken to be used in the analysis. After the two-minute time period was completed, collected liquid samples were taken. In the case of the double collector, this involved using the two riser spigots and the two collection tanks, whereas tests with either the single collector or the riser alone without a collector involved a single riser spigot and a single collection tank. The spigots were swung over a collection tank and a stop-watch was started. After approximately 1.5 cubic meters were collected in a collection tank, the riser spigot was swung away and the stopwatch was stopped.

The collection flow rate from each riser was determined by dividing the stopwatch time into the volume of the collected liquid. Samples of the collected liquid were taken from the collection tanks for subsequent analysis. Figure 8 is a photograph of an operating riser spigot.

4. INTERMEDIATE SCALE TEST DATA ANALYSIS AND DATA REDUCTION

Data analysis involved determination of the fraction of the dye delivered to the wellhead that was recovered. This is representative of the fraction of oil from a blowout that would be collected for similar conditions.

The following symbols will be used for a single riser system:

c_d = dye concentration in dye tank,

c_a = dye concentration in collected liquid,

Q_d = liquid flow rate of dye delivered to the wellhead,

Q_a = liquid flow rate in riser.

For the double collector system which contained two operating risers, all of the above variables apply with the subscript "a" referring to quantities associated with the inner riser and with the addition of the following quantities:

c_b = concentration of dye in liquid coming from outer riser,

Q_b = liquid flow rate in outer riser.

For the single riser system, the fraction, f_a, of blowout liquid collected is given by

$$f_a = \frac{c_a Q_a}{c_d Q_d} = \frac{c_a}{c_1} \tag{3}$$

where the reference concentration c_1 is given by

$$c_1 = c_d (Q_d / Q_a) \tag{4}$$

For a double riser system, f_a is the fraction of blowout oil collected by the inner riser with the fraction collected by the outer riser being given by

$$f_b = \frac{c_b Q_b}{c_d Q_d} = \frac{c_b}{c_2} \qquad (5)$$

where the reference concentration c_2 is given by

$$c_2 = c_d(Q_d/Q_b) \qquad (6)$$

The fluorometer was set up to provide a measure of the concentration of a sample with respect to two reference concentrations c_ℓ and c_u. The concentration scale that these provide is 0 for c_ℓ and 1.0 for c_u. For each measurement, the collected water sample before dye pumping began was used for c_ℓ. These are called "bottom water samples". The value used for c_u in each measurement was either c_1 or c_2, depending on which riser flow was being analyzed. These samples, having concentrations c_u, were prepared by diluting the sample of dye tank liquid with the bottom water sample according to the dilutions specified by equations (4) and (6).

In the case of the double collector system, the total collected fraction for each case was determined by adding f_a and f_b. The collected blowout liquid percentages (100 x collected fraction) are shown in Table 5 along with the test flow rates.

For each test condition, the Froude number and phase ratio were calculated in accordance with equations (1) and (2). For the double collector system, the two riser flow rates were added together to determine Q_T. The gas flow rate was taken from the orifice meter readings and calculations. This is representative of the gas flow rates within the systems having collectors. However, for the test having only a riser without a collector on its bottom some of the gas escaped beside the riser so that the average phase ratio in the riser is higher than the calculated values for R with this particular system.

The data interpolation function given by equation (2) of Part I is based on a phase ratio determined from the gas flow rate at a pressure of 1 atmosphere. That interpolation function is satisfactory for all of the measurements described in Part I because they were all taken at the same water depth. However, for comparing the laboratory scale measurements with the intermediate scale measurements, it is necessary to consider gas flow rates at the collector entrance inasmuch as it is this quantity that influences the fluid mechanics in the collector. Henceforth, the phase ratio R will be considered on the basis of the gas flow rate at the collector, which is the gas flow rate at a pressure of 1 atmosphere multiplied by the ratio of 1 atmosphere to the absolute pressure at the collector entrance. In order to adjust equation (2) of Part I for phase ratios calculated in this way it is only necessary to modify the coefficient B to its previous value multiplied by the ratio of absolute pressure at the bottom to that at the surface. For the laboratory experiments this ratio is 1.33 so that the value for B of 1.41879 for use with air flow rates at the surface becomes 1.88699 for use with air flow rates at the collector entrance.

The interpolating function of Part I fit the laboratory data with an RMS error of 8.7%. Applying the same function to the intermediate scale data showed an RMS error of 10.9%. A study was made to determine why this was larger than the 8.7% found with the laboratory data for which the interpolating function was constructed; and to generate a new interpolating function that could be more accurately applied to all of the laboratory and intermediate scale data simultaneously. Two scale-dependent phenomena were identified.

Observations of gas bubble plumes in our laboratory have shown that immediately above the wellhead, the plume has a rather cylindrical shape. Its generally conical form begins a small distance above the wellhead with the projected apex of the cone lying above the wellhead. Dr. David Topham (private communication) has found a similar result and ascribes it to the fact that the plume does not entrain much surrounding water until the bubbles emanating from the wellhead burst for the first time, with this occurring some distance above the wellhead. This phenomenon can be included in an interpolating function by using a modified Froude number F' in lieu of the Froude number F where

$$F' = Q_T/[g(h + D')^5]^{\frac{1}{2}} \qquad (7)$$

The quantity D' must have the same order of magnitude as the distance between the wellhead and the height at which bubbles first burst. For this analysis, it is taken as a constant to be determined such that the interpolating function gives the best fit to all of the data. This will be done subsequently.

The second scale-dependent phenomenon is the ratio between the bubble size and the length scale. The fundamental length scale of the buoyant gas flow is called L_A and is given by

$$L_A = Q_A^{0.4}/g^{0.2} \qquad (8)$$

where Q_A is the gas volume flow rate at the collector entrance. The length scale of the bubbles is called L_B and is given by

$$L_B = \sqrt{\frac{T}{\rho_w g}} \qquad (9)$$

where T is the gas-liquid surface tension (taken here as 0.072 Newtons/meter) and ρ_w is the mass density of water (taken here as 1000 Kg/m^3).

An increase in the amount of gas (a lower phase ratio) reduces oil collection efficiency as is described in Part I. This is accounted for in the interpolating function through the effect of the phase ratio, R. The scale-dependent effect of bubble size is included in the new interpolating function by replacing the phase ratio R with a modified phase ratio R' given by

$$R' = R\left(1 + E' \frac{L_B}{L_A}\right) \qquad (10)$$

The dimensionless constant E' is to be determined so that the best fit between all of the data and the interpolating function is obtained.

The new interpolating function was taken as the same form as for Part I, except for the use of the modified Froude number and phase ratio. Thus the new functional form is

$$P = 100 \times \left[1 - \exp\left(\frac{-A' \times R' \times F'}{B' + R'}\right)\right]^{C'} \qquad (11)$$

where P is the percentage of blowout liquid collected and the A', B', C', D' and E' are constants.

Their values were determined to minimize the RMS error between equation (11) and the single collector laboratory and Bugg Spring data together. These are:

$$\begin{aligned} A' &= 59.69 \\ B' &= 6.991 \\ C' &= 0.3726 \\ D' &= 0.1112 \text{ meters} \\ E' &= 11.77 \end{aligned} \qquad (11\ a,b,c,d,e)$$

The standard deviation over all of these data points between the interpolating function and the measurements is 8.2% which is an improvement over the 8.7% for the application of the weighting function in Part I to only the laboratory scale data. In applying the new interpolating function to the intermediate scale (Bugg Spring) data only, the standard deviation is 8.4%.

A set of smooth curves of fraction collected versus Froude number for various phase ratios based on the new interpolating equation (11) is shown in Figure 9. Table 5 shows the actual percentages collected in the intermediate scale tests of the single collector as well as the predictions of equation (11) for each test condition with the single collector. For purposes of comparison the results for the double and "riser only" collectors are presented in Table 5 along with the predictions of equation (11) for a single collector operating at the same Froude numbers and phase ratios (based on the total liquid and gas flows).

A result of having done experiments at two different scales is that two scale-dependent effects were able to be identified and included in the smoothing function for fraction of blowout oil collected. With these included, the standard deviation between all single collector measurements, both at laboratory and at intermediate scales, and the new smoothing function is 8.2%, which is probably representative of the overall experimental accuracy. It is anticipated that the new smoothing function as given by equations (7) and (10) through (11) is representative of full-scale collection efficiency for any anticipated gas flow rate, riser flow rate and collector height.

The advantage of the double collector over the single collector has been clearly demonstrated both in the laboratory and at intermediate scale. Naturally, under conditions where a single collector is efficient there is little to be gained by use of a double collector. However, under conditions where the efficiency of a single collector is rather low, very marked gains in collection efficiency are possible through use of a double collector. For conditions under which a single collector would collect less than 40% of the blowout oil, use of a double collector can result in collecting up to about twice as much oil.

Use of a riser alone without a collector has an efficiency that is approximately the same as a single collector. However, there are some substantive differences in the fluid mechanical details. Much more gas remains uncollected with the "riser only" system. Thus the phase ratio in the system is higher than that calculated for a single collector operating at the same collected liquid rate and wellhead gas flow rate. Laboratory tests have shown that a small single collector that "spills" some of the gas, but less gas than a "riser only" system, is more efficient than either a "riser only" system or a single collector that spills no gas. Evidently there are two features of the "riser only" system whose effects on collection efficiency approximately counterbalance each other. One is the gain in efficiency associated with less gas in the collector entrance. The other is the loss in efficiency due to some of the plume passing up beside and outside of the riser.

Reference

1. Research and Development Program, Conservation Division Technical Report 1981, U.S.G.S. Open-File Report 81-704.

Froude Number	Phase Ratio	Double Collector	Single Collector
0.009	0.033	86	36
0.014	0.18	81	39
0.018	0.66	95	69
0.019	0.35	90	52
0.021	0.26	68	54
0.022	0.10	47	35
0.022	0.21	58	53
0.066	0.30	82	75
0.072	0.16	70	63
0.14	0.64	94	59
0.17	0.22	90	88
0.17	0.37	94	93

Table 1. Laboratory Results for Tests With the Double Collector. The comparative single collector percentages are the predictions from equation (2) of Part I for the same Froude number and phase ratio.

Test Number	Height Above Wellhead (m)	Air Flow Rate (nm^3/s)	Dye Flow (liters/s)	Inner Riser Flow (m^3/s)	Outer Riser Flow (m^3/s)	% of Dye Collected
1	2.25	0.047	2.59	0.064	0.000	74
2	0.04	0.047	2.36	0.084	0.000	118
3	0.04	0.047	2.06	0.065	0.000	88
4	2.25	0.165	1.03	0.149	0.110	60
5	2.25	0.165	2.25	0.139	0.097	64
6	0.04	0.165	2.50	0.138	0.000	93
7	1.19	0.165	2.46	0.130	0.030	90
8	1.19	0.165	2.54	0.038	0.026	89
9	1.19	0.165	2.59	0.092	0.016	87
10	2.25	0.165	2.10	0.174	0.029	74
11	2.25	0.557	2.13	0.030	0.016	44
12	2.25	0.614	2.08	0.027	0.016	36
13	2.25	0.614	2.07	0.146	0.017	54

Table 2. Test Conditions for the Double Collector.

Test Number	Height Above Wellhead (m)	Air Flow Rate (nm^3/s)	Dye Flow (liters/s)	Riser Flow (m^3/s)	% of Dye Collected
1	1.19	0.047	1.08	0.102	87
2	1.19	0.047	2.10	0.104	84
3	0.04	0.047	2.13	0.102	100
4	1.72	0.047	1.37	0.104	80
5	0.04	0.165	2.28	0.136	88
6	1.19	0.165	2.26	0.138	80
7	1.19	0.165	2.25	0.079	63
8	1.19	0.165	2.25	0.040	56
9	0.64	0.165	2.25	0.136	96
10	0.64	0.165	2.25	0.039	57
11	0.64	0.165	2.25	0.077	91
12	0.04	0.550	1.99	0.147	94
13	1.19	0.590	2.13	0.115	65
14	1.19	0.590	2.11	0.051	32
15	1.72	0.590	0.88	0.155	40
16	1.72	0.590	0.95	0.052	14

Table 3. Test Conditions for the Single Collector.

Test Number	Height Above Wellhead (m)	Air Flow Rate (nm^3/s)	Dye Flow (liters/s)	Riser Flow (m^3/s)	% of Dye Collected
1	1.19	0.047	1.11	0.101	99
2	1.19	0.047	2.32	0.104	100
3	0.04	0.047	2.27	0.104	111
4	1.72	0.045	2.27	0.094	97
5	0.04	0.165	2.28	0.134	88
6	1.19	0.165	2.28	0.141	75
7	1.19	0.165	2.27	0.064	50
8	0.64	0.165	2.27	0.138	80
9	0.64	0.165	2.26	0.064	59
10	0.04	0.578	2.08	0.043	72
11	1.19	0.590	2.16	0.131	53
12	1.19	0.590	2.17	0.048	31
13	1.72	0.590	2.11	0.139	34
14	1.72	0.590	2.17	0.043	20

Table 4. Test Conditions for the Riser Alone Without a Collection Cone on Its Bottom.

DOUBLE COLLECTOR

NO.	F	R	TEST %	PREDICTED %
1	0.003	7.728	74.	42.
2	71461.875	9.737	118.	100.
3	55044.949	7.500	88.	100.
4	0.011	8.933	60.	67.
5	0.010	8.159	64.	64.
6	117332.625	4.579	93.	100.
7	0.034	5.270	90.	84.
8	0.031	4.770	89.	81.
9	0.023	3.510	87.	71.
10	0.013	3.153	73.	59.
11	0.004	0.874	44.	26.
12	0.003	0.651	36.	22.
13	0.012	2.569	54.	54.

SINGLE COLLECTOR

NO.	F	R	TEST %	PREDICTED %
1	0.023	12.120	87.	83.
2	0.023	12.322	84.	84.
3	87154.500	11.875	100.	100.
4	0.016	22.466	80.	80.
5	115884.125	4.523	88.	100.
6	0.031	4.684	80.	80.
7	0.017	2.674	63.	62.
8	0.009	1.366	56.	42.
9	0.172	4.550	96.	100.
10	0.044	1.314	57.	70.
11	0.086	2.571	91.	92.
12	125541.125	1.472	94.	100.
13	0.025	1.093	65.	55.
14	0.011	0.482	32.	32.
15	0.013	1.483	40.	48.
16	0.004	0.500	14.	23.

RISER ONLY

NO.	F	R	TEST %	PREDICTED %
1	0.022	11.919	99.	83.
2	0.023	12.355	100.	84.
3	88603.062	12.072	111.	100.
4	0.008	11.284	97.	62.
5	114194.125	4.457	88.	100.
6	0.031	4.770	75.	81.
7	0.014	2.183	50.	56.
8	0.155	4.629	80.	99.
9	0.073	2.162	59.	87.
10	36213.785	0.404	72.	100.
11	0.029	1.241	53.	60.
12	0.011	0.452	31.	31.
13	0.012	1.328	34.	45.
14	0.004	0.416	20.	20.

Table 5. Measured Percentages of Blowout Oil.
In addition to measured percentages for each condition, the Froude Number (F), Phase Ratio (R) and percentage predicted by equation (5.9) are shown. These are for a single collector so they provide a basis for comparison of the other systems.

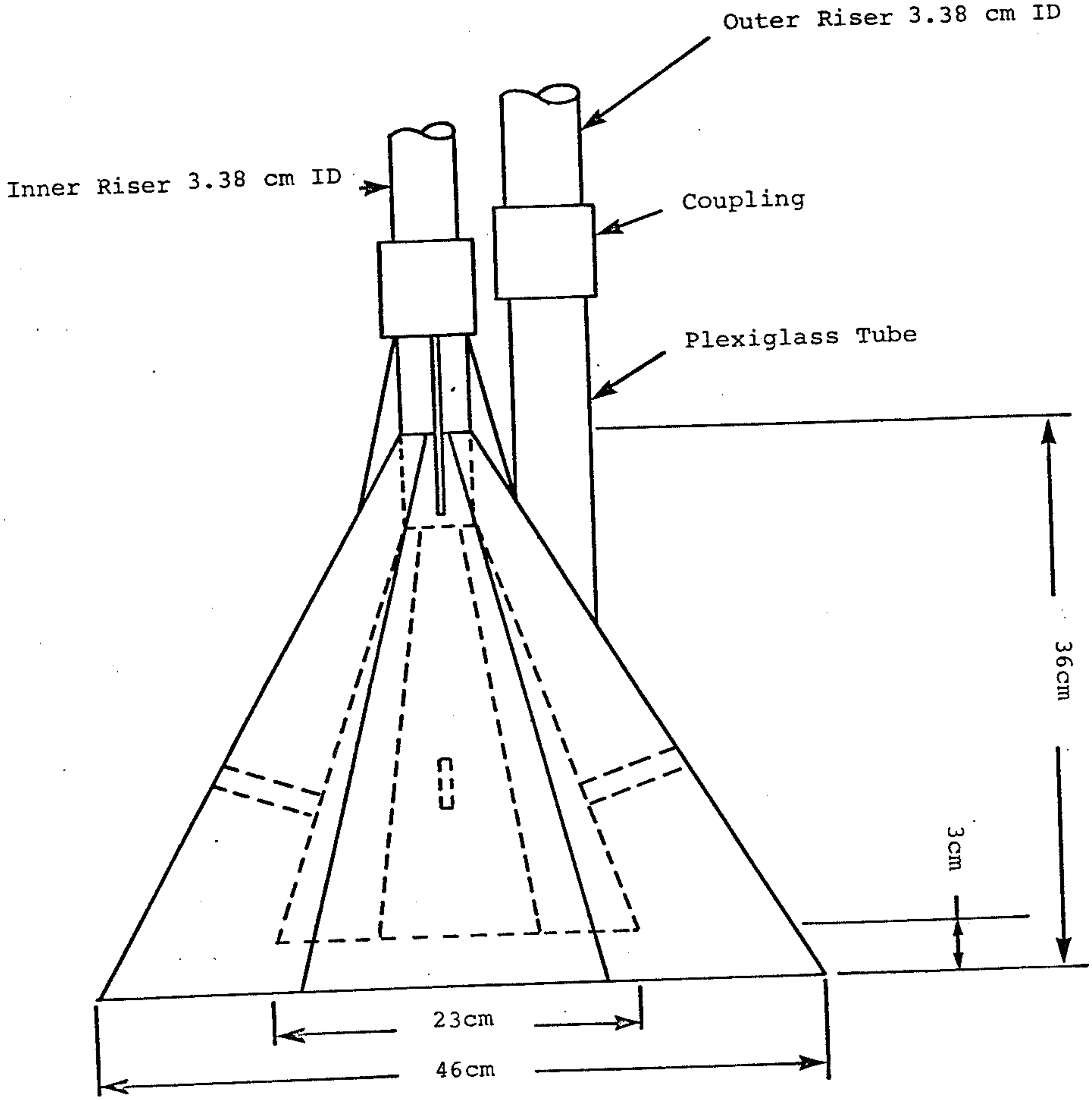

Figure 1. The Double Collector with Two Risers of the Same Diameter which was Tested in the Labortory.

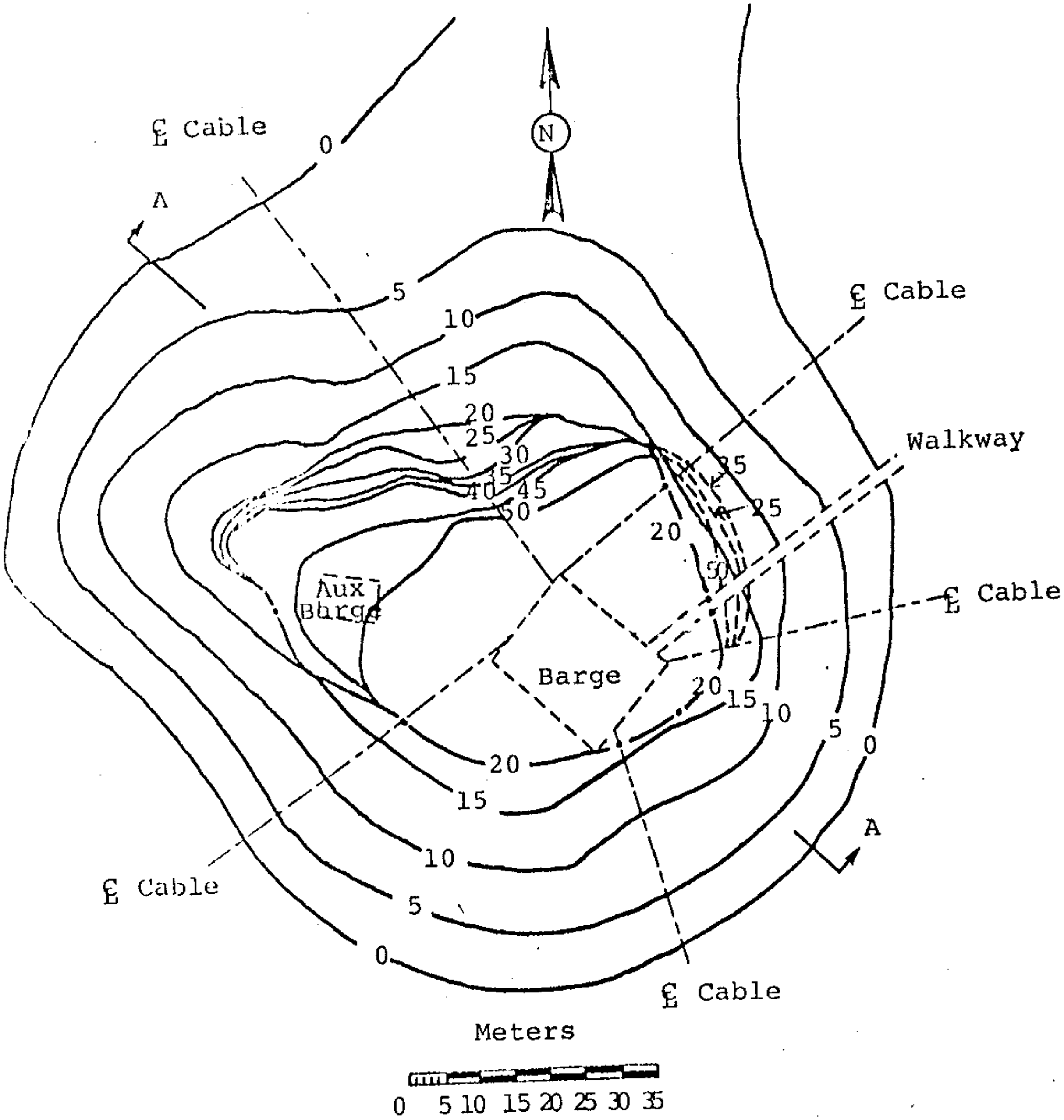

Figure 2(a). Contour Plan of Bugg Spring.

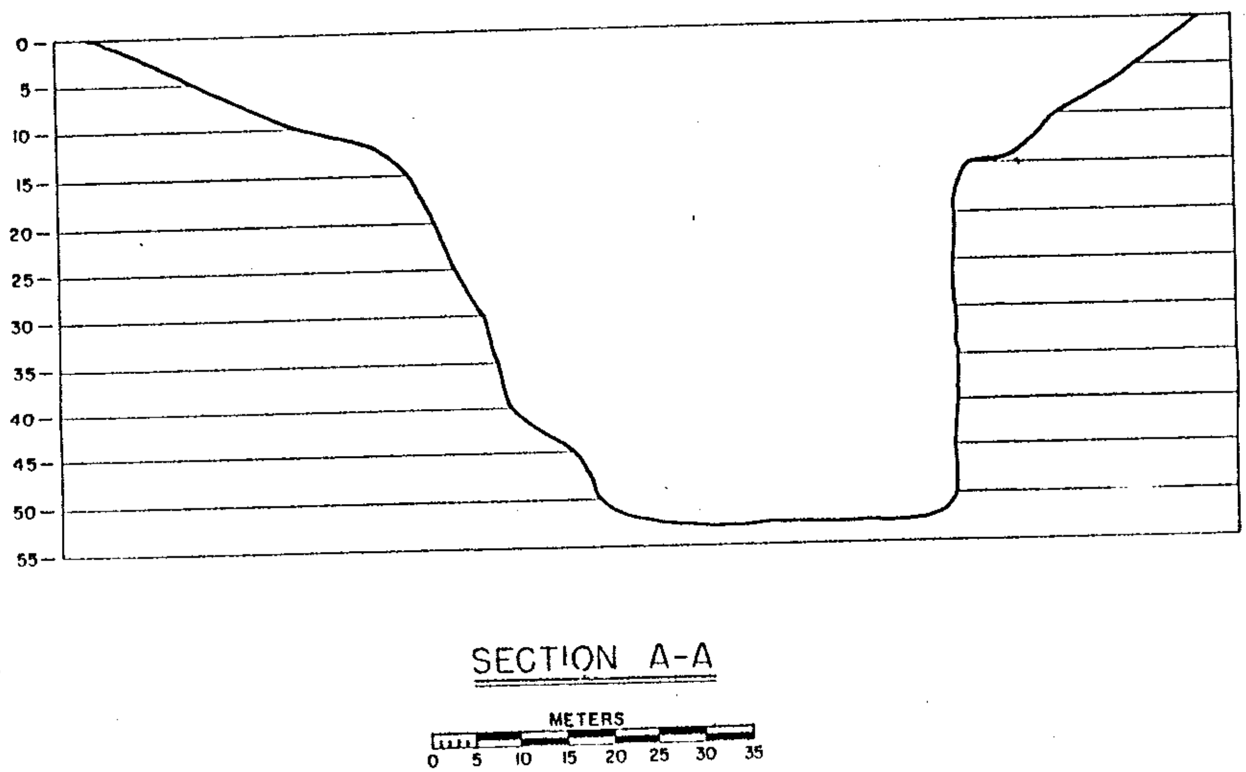

Figure 2(b). Cross-Sectional Depth Profile of Bugg Spring.

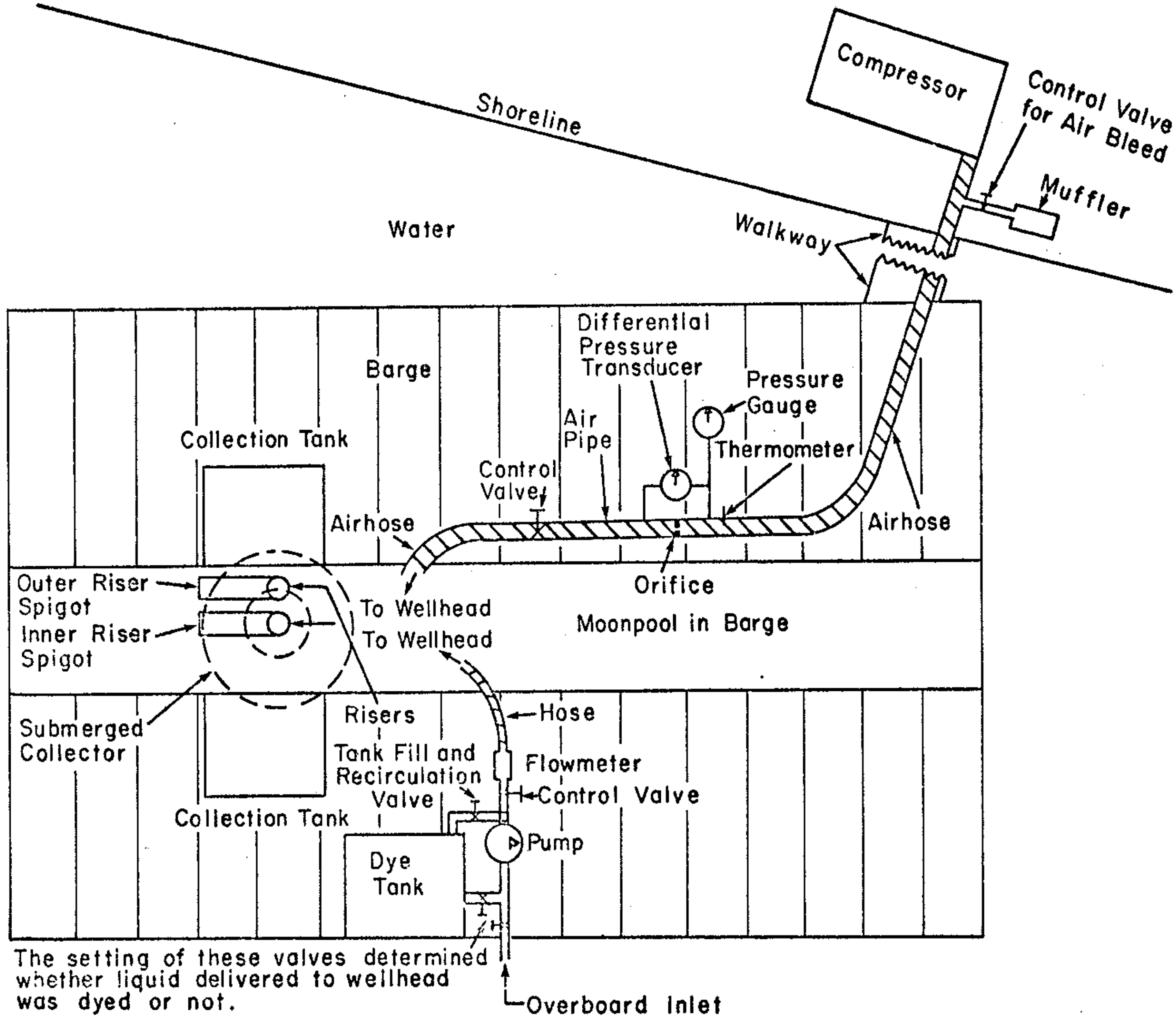

Figure 3. Overall Arrangement for the Intermediate Scale Tests.

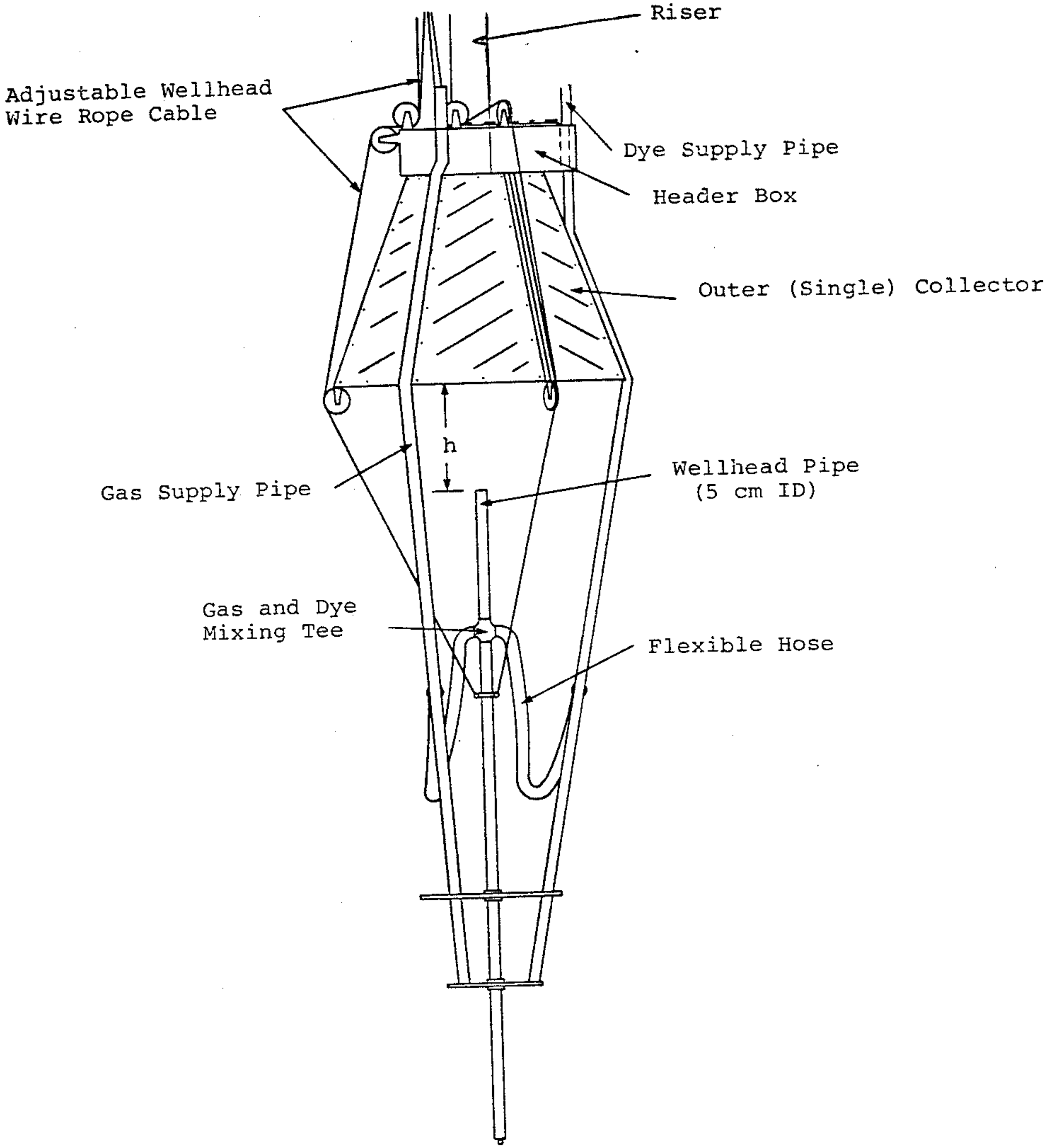

Figure 4. Collector-Wellhead Assembly with Single Collector.

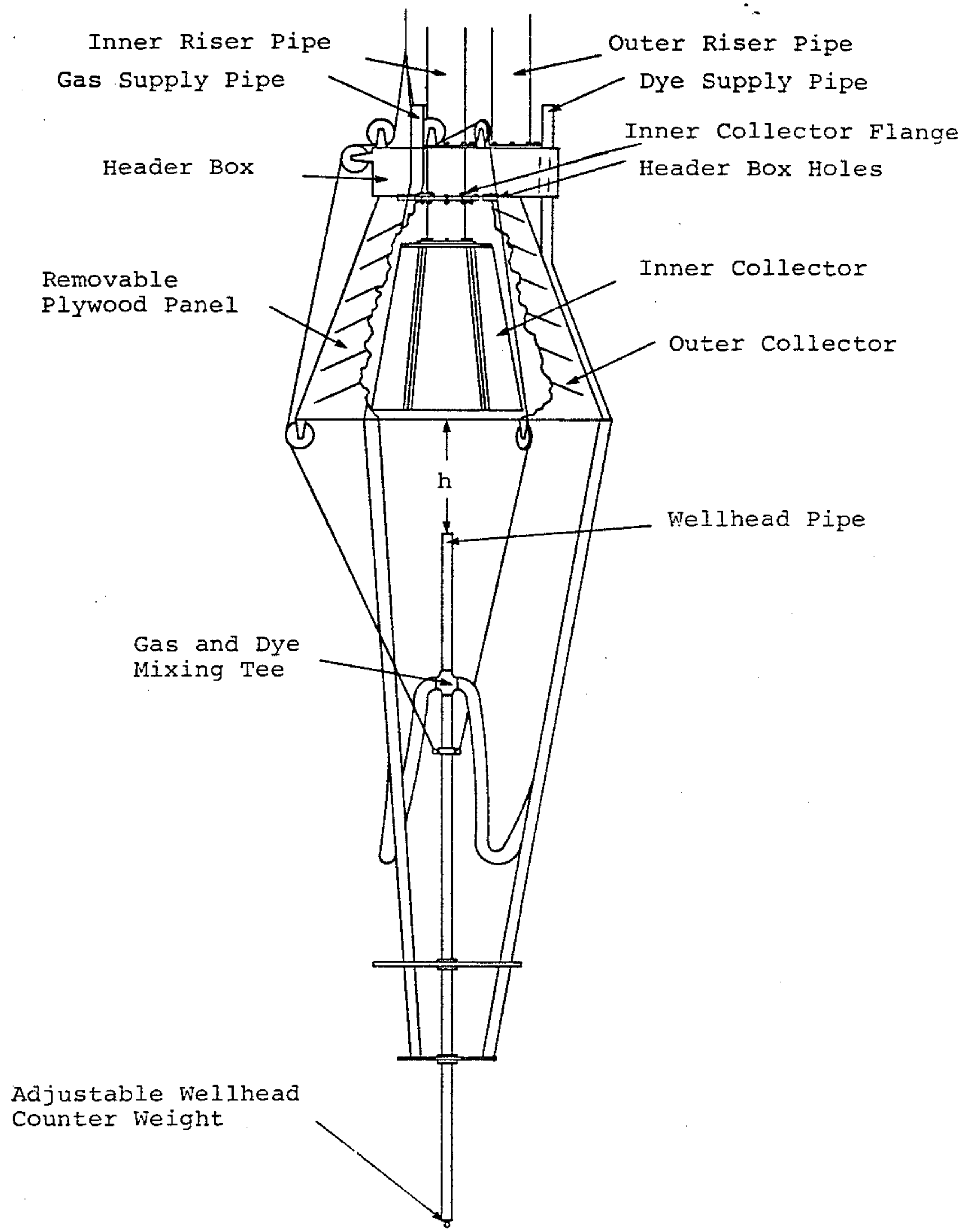

Figure 5. Details of Double Collector.

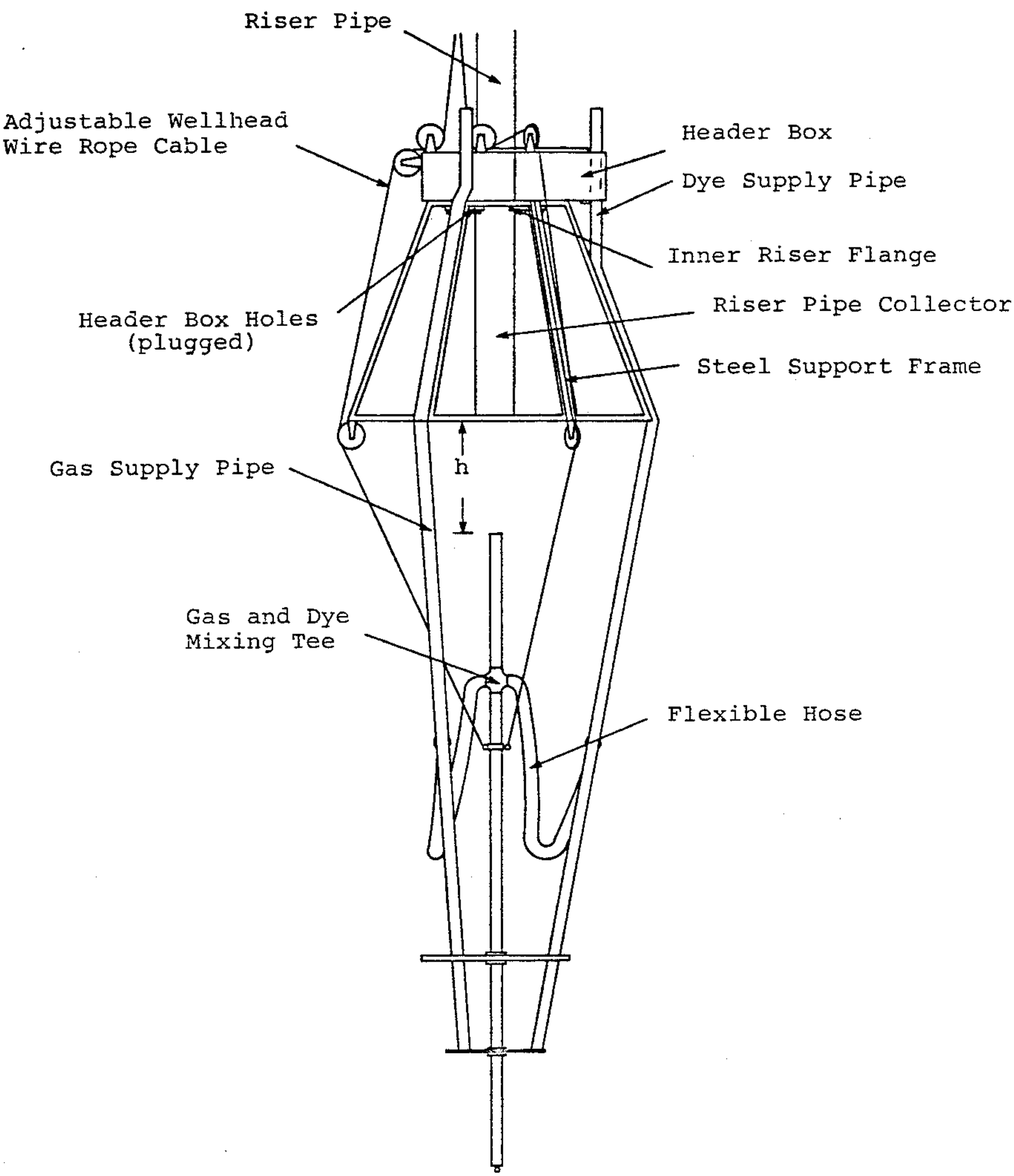

Figure 6. Single Riser Pipe Collector.

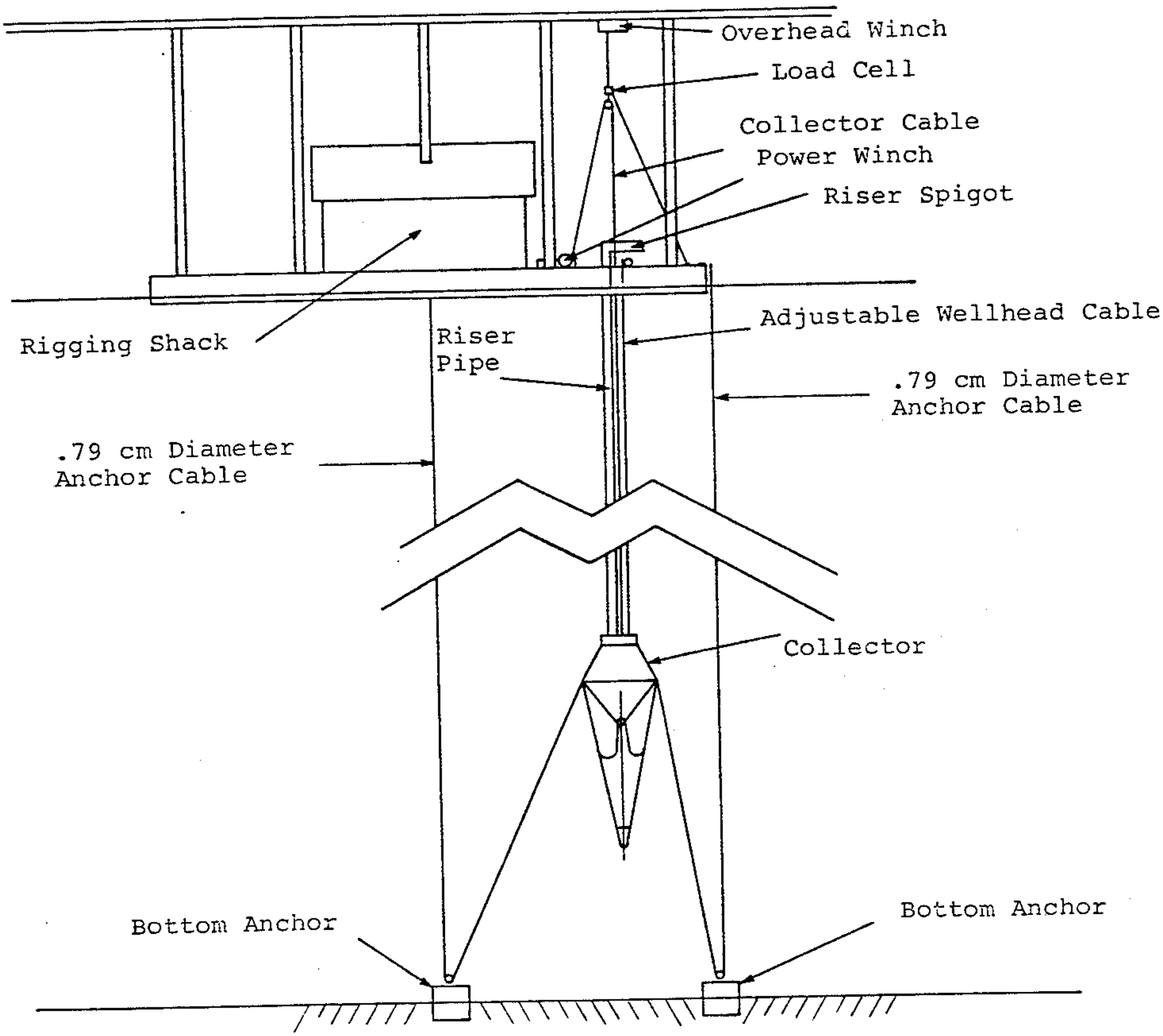

Figure 7. Mooring System. Three bottom anchors were used although only two are shown in this view.

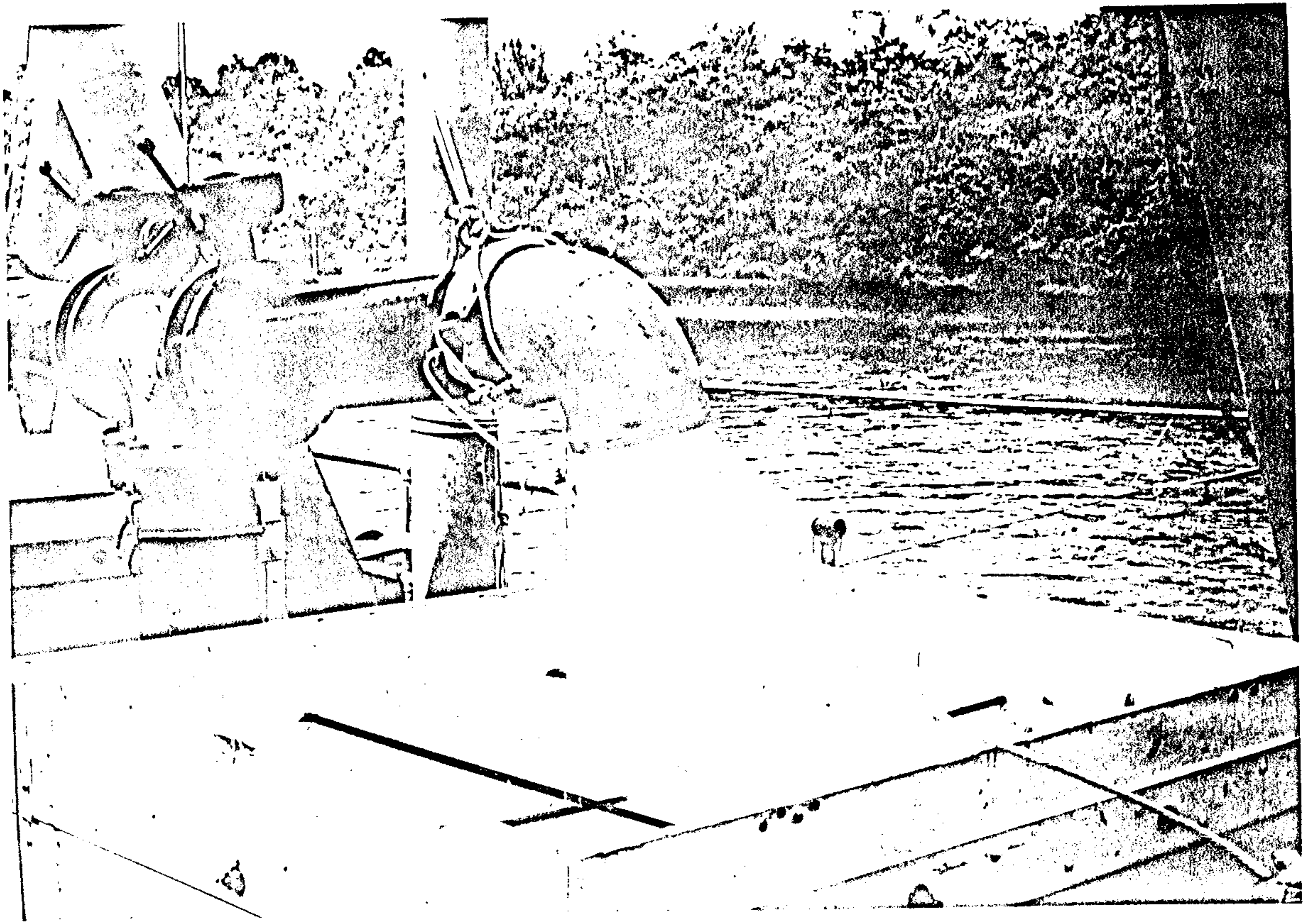

Figure 8. An Operating Riser Spigot

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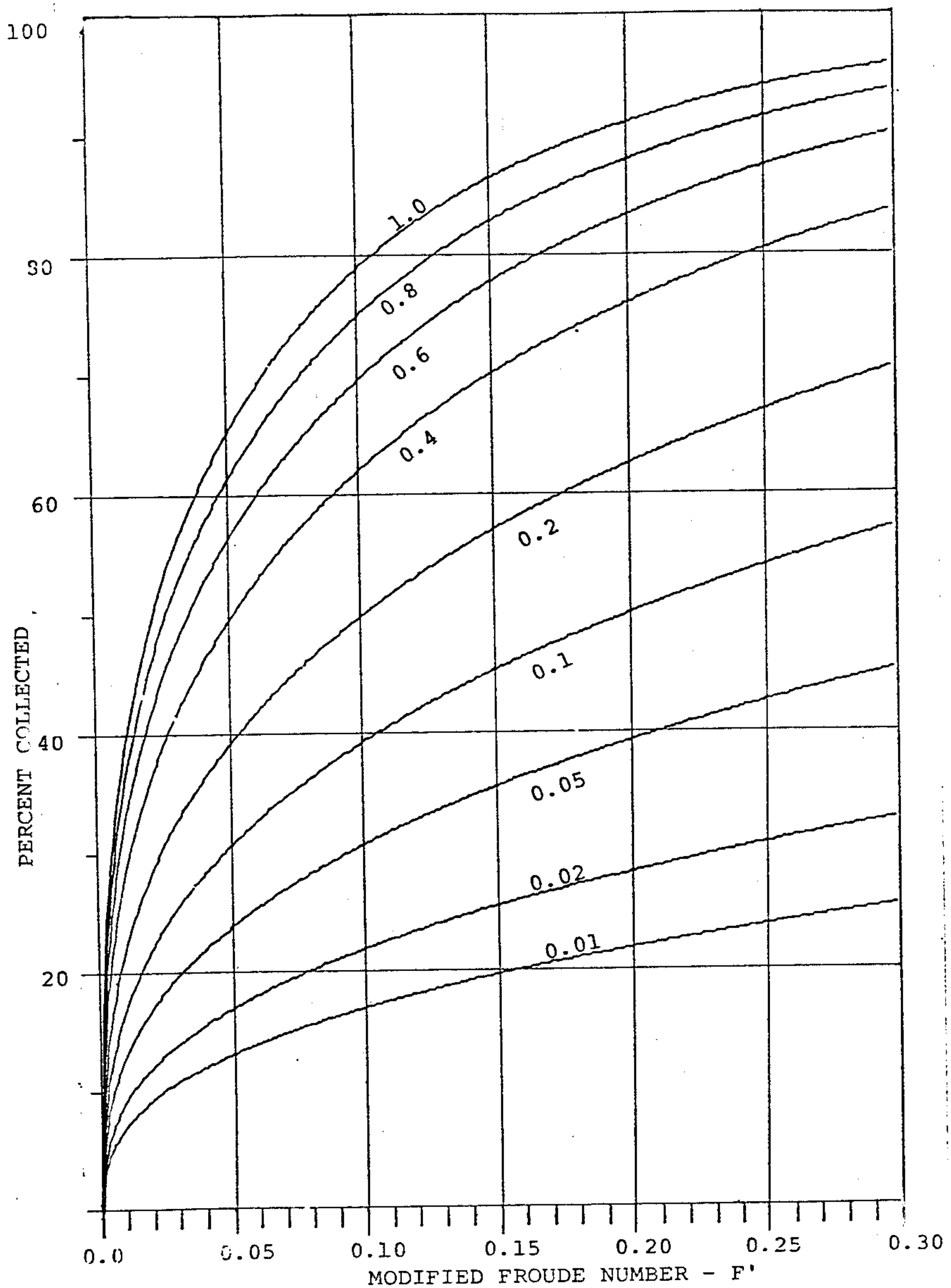

FIGURE 9. Percent Oil Collected vs. Modified Froude Number Using Equation 5.9 with: A'=59.69, B'=6.991 and C'=0.3726. The number on each curve is the modified phase ratio, R'.